

P-CHANNEL TRENCH MOSFET STRUCTURERELATED APPLICATIONS

This application is related to copending application Serial No. 08/299,533, filed September 1, 1994 entitled PROCESS FOR MANUFACTURE OF MOS GATED DEVICE WITH REDUCED MASK COUNT <sup>now U.S. Patent 5,795,793</sup> ~~IR 1113~~; and application Serial No. 60/104,148, filed October 14, 1998 entitled MOSGATED DEVICE WITH TRENCH STRUCTURE AND REMOTE CONTACT AND PROCESS FOR ITS MANUFACTURE (IR-1461). B

BACKGROUND OF THE INVENTION

This invention relates to power MOSgated devices and more specifically relates to a novel low voltage P-channel MOSFET having a reduced switching loss.

Power Mosgated devices are well known and include such devices as power MOSFETs; IGBTs; gate controlled thyristors and the like. In low voltage applications of such devices, particularly in connection with battery operated portable electronic devices, such as personal computers, cellular telephones and the like, frequently termed wireless systems, careful power management is essential to extend the battery life and its usage between charges.

Power management applications in wireless systems fall generally into two categories. One category is charging the battery from an external DC source. It is important to control both the charging current and voltage correctly for the particular battery technology. This control is accomplished by modulating the duty cycle of a transistor placed between the power source and the battery in well known ways. The second category activates a portion of the system on demand. In this

case the transistor is placed between the battery and the load to be activated, such as an RF power amplifier. In some systems, multiple power supply voltages require DC/DC conversion as well. This may be accomplished with well known low dropout linear regulators or buck and boost switching regulators.

Both N-channel and P-channel power MOS transistors as the transistor in the above applications are available. P-channel devices are generally easier to use in these circuits. Thus, when the P-channel MOSFET is placed in the power bus, it can be controlled with a logic input that switches between the power rail and ground. This allows a single uninterrupted ground for the whole system. N-channel devices in the power bus require a gate signal that is boosted to a voltage higher than the bus, which requires extra circuitry.

In the past, the simplicity of a P-channel device came at the price of increased losses. This is because P-channel devices rely on hole conduction, and holes have a lower carrier mobility in silicon than electrons. The on-resistance of the active transistor is proportional to the carrier mobility, and its losses are proportional to the on-resistance,  $R_{DS(on)}$ .

To overcome this limitation, the length of the resistive path should be minimized and the width maximized within the transistor. The number of holes in the path must also be maximized. One way to do this is to lower the maximum voltage rating as much as possible which permits the use of lower resistivity and higher dopant concentration silicon.

Since most batteries operate at only a few volts, a 12V rating is generally more than enough for a transistor in a wireless application. Previously

available devices are rated at 20V, and have a reasonably low value of  $R_{DSON}$  at 2.5V gate to source. These parts come in various die sizes and package styles, ranging from the Micro 3 (SOT23) up to the SO8. The values listed in the following Table are for single transistors in a package, though the Micro 8 and SO8 packages also have dual versions. The power loss using these devices can be as high as 9% which translates directly into reduced usage.

Load Current	Part Number	Package Style	$R_{DSON}$ @ 2.5V	$V_{drop}$ or $P_{diss}$ (as % of 5V supply)
500 mA	IRLML6302	Micro 3™	0.9 Ω	9%
1 A	IRLMS6702	Micro 6™	0.4 Ω	8%
2 A	IRF7604	Micro 8™	0.13 Ω	5%
4 A	IRF7416	SO-8	0.035 Ω	3%

It is known that a low voltage power MOSFET can be made with trench type technology to obtain reduced  $R_{DSON}$ , gate to drain capacitance, and to reduce  $Q_g$  (gate charge). Switching losses are proportional to the product of the device  $R_{DSON}$  and  $Q_g$  so it would be desirable to also reduce  $R_{DSON}$  in such devices. The present P-channel trench type power MOSFET uses a P-type substrate with a P-type epitaxial layer thereon. The device channel regions are formed by deep N-type diffusions from the top surface of the epitaxial layer, followed by P-type source diffusions. The voltage is then mostly blocked in the P-type epitaxial layer, resulting in a fairly large resistive drop, and in

increased losses in a wireless system. These losses in turn reduce battery life between charges.

BRIEF DESCRIPTION OF THE INVENTION

In accordance with the invention, in a P-channel trench type MOSgated device, the conventional P-type substrate epitaxial layer is eliminated and the diffused channel is replaced by an epitaxially grown N-type channel region. The channel region now has a uniform concentration, and the relatively lower doping of the channel region allows voltage to be blocked in the channel region and reduces the threshold voltage  $V_T$  for turn-on. Thus, with the novel structure, a major component of the on-resistance is removed and the device can be completely turned on at a gate to source voltage of 2.5 volts.

When the novel die of the invention is packaged in the same packages reported in the above Table, the  $R_{DS(ON)}$  and power loss has been reduced up to 4 times, as shown in the following Table:

Load Current	Part Number	Package Style	$R_{DS(ON)}$ @ 2.5V	$V_{drop}$ or $P_{diss}$ (as % of 5V supply)
500 mA		<i>Micro 3</i> <sup>TM</sup>	0.18 $\Omega$	1.8%
1 A		<i>Micro 6</i> <sup>TM</sup>	0.075 $\Omega$	1.5%
2 A		<i>Micro 8</i> <sup>TM</sup>	0.025 $\Omega$	1%
4 A		SO-8	0.010 $\Omega$	.8%

Thus, as shown above, overall circuit losses are reduced to less than 2% even at the discharged battery 2.5 volt condition.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Figure 1 is a cross-sectional view of the junction pattern of a single cell of a prior art type of trench type P-channel MOSFET.

10 Figure 2 is a cross-section like that of Figure 1, but illustrates the junction pattern and structure of the present invention.

15 Figure 3 shows a circuit diagram of two MOSFETs like those of Figure 1 or 2, connected to form a bidirectionally conductive device.

20 Figure 4 is a cross-section similar to that of Figure 2, but shows a revised junction pattern by which a bidirectional MOSFET is formed.

25 Figure 5 is a circuit diagram of the bidirectional FET of Figure 4.

Figure 6 is a top view of a portion of the silicon substrate used to make the device of Figure 2.

30 Figures 7, 8, 9 and 10 show the appearance of the cross-section of the silicon of Figure 6, taken across section line 7-7 in Figure 6, following various process steps.

25 DETAILED DESCRIPTION OF THE DRAWINGS

Referring first to Figure 1, there is shown one "cell" of a prior art P-channel trench type MOSFET. The single cell shown will be replicated any number of times over the surface of a chip.

30 Thus, the device has a P<sup>+</sup> doped substrate 20 which has an epitaxially deposited, lightly doped P-

layer 21 thereon. An N<sup>+</sup> channel diffusion 22 is diffused into the upper surface of P<sup>-</sup> layer 21 and is, therefore a graded diffusion. Trenches such as spaced trenches 23 and 24 are etched into the upper surface of the wafer or chip which is shown and extend below the bottom of channel diffusion 22. These trenches are lined with a gate insulation layer, such as an oxide, shown as gate oxide layers 25 and 26 in trenches 23 and 24 respectively and are filled with conductive polysilicon gates 28 and 29 respectively which are connected to one another (not shown) and to a common gate electrode. P<sup>+</sup> source diffusions 30, 31, 32 and 33 are formed at the top of trenches 23 and 24 respectively. Note that trenches 23 and 24 may be elongated stripe structures and that source regions 30 to 33 will also be elongated stripes. However, trenches 23 and 24 may also be polygonal in topology, in which case, the P<sup>+</sup> sources will surround ~~respective~~ trenches. Trenches may also surround the polygonal P<sup>+</sup> sources. Oxide insulation plugs 35 and 36 overlie polysilicon stripes 28 and 29 and insulate the polysilicon stripes from an overlying aluminum source contact 40. Source contact 40 contacts source regions 30, 31, 32 and 33 as well as the channel diffusion 22 in the usual manner. A drain contact 41 is connected to the bottom of the die to complete the vertical conduction trench device.

In operation, a sufficiently high gate voltage must be applied to polysilicon gates 28 and 29 to cause the graded channel diffusion 22 to invert along its entire length from sources 30 to 33 to the P<sup>-</sup> epi layer 21. Thus, a relatively high gate voltage is needed to ensure inversion of the higher concentration portions of the channel diffusion. Further, once the device is

B turned on, carriers flowing between drain 41 and source 40 see the relatively high resistance  $R_{\text{epi}}$  of layer 21, thus causing an increased  $R_{\text{DS}ON}$  for the devices.

5 The present invention provides a novel structure which permits the use of a lower gate voltage and which has a lower  $R_{\text{DS}ON}$  in a P-channel trench type MOSgated device. This device is shown in Figure 2 where components similar to those of Figure 1 have the same identifying numerals.

10 It will first be noted that the source contact in Figure 2 is made to  $P^+$  source stripes 30, 31, 32 and 33 in the manner shown in copending application (IR-1113) Serial No. 08/299,533. Thus, a notch 50, for example, is etched through the  $P^+$  source stripes to enable the source 15 electrode 40 to contact the  $P^+$  source stripes 31-33 and the underlying N-type channel regions. An  $N^{++}$  diffusion 51 may also underlie the bottom of the control notch to improve the contact between aluminum source 40 and silicon 60.

20 In accordance with the invention, the graded channel diffusion 22 and  $P^-$  epi layer 21 of Figure 1 are replaced by an  $N^+$  epitaxially grown layer 60, grown directly on  $P^+$  substrate 20. The  $N^+$  layer 60 has a constant concentration along its full depth (a zero 25 vertical gradient), and receives the various trench structures 23, and 24. Its concentration is selected to provide a low threshold voltage  $V_T$ .  $P^+$  sources 30 to 33 are diffused into the top of  $N^+$  epi layer 60.

30 As a result of the new structure, a reduced threshold voltage can be obtained, to allow about 2.5 volts to turn the device fully on, because the concentration along the full length of the invertible

layer adjacent the trench side walls is uniformly low. Further, the on resistance of the device is reduced because the resistance component  $R_{epi}$  in Figure 1 is removed from the device of Figure 2.

5        The device of Figures 1 or 2 can also be made as a bidirectional MOSFET as shown in Figure 4 for the device of Figure 2. Thus, the device of Figure 4 is identical to that of Figure 2 except that the source contact 40 contacts only the P<sup>+</sup> source regions 30-33, and  
10      does not contact channel region 60.

15      The structure of Figure 4 provides a single bidirectional MOSFET using less silicon area and having less on-resistance than that of two series connected MOSFETs such as those of Figures 1 and 2 to create a  
20      bidirectionally controlled circuit. Thus, in the past, two vertical conduction MOSFETs 70 and 71 must be connected in series between terminals 72 and 73, and will have a common gate terminal 74 to permit bidirectional control of circuit at terminals 72 and 73, as shown in Figure 3. By contrast, as shown in Figure 5, device 80, which is the device of Figure 4, will provide  
25      bidirectional control between terminals 72 and 73. However, the device and circuit of Figures 4 and 5 will have one-half of the  $R_{DS(on)}$  of the circuit of Figure 3, and will have one half of the silicon area.

Figures 6 through 10 describe a preferred process to manufacture the device of Figure 2. Similar numerals of Figures 1 and 2 describe similar elements in Figures 6 through 10.

30      The starting wafer for the process for a 12 volt P-channel device is a boron doped P<sup>+</sup> substrate 20 having a resistivity of less than 0.005 ohm cm and a thickness of 375  $\mu$ m. An N<sup>+</sup> epitaxial layer 60 is grown

atop substrate 20 and is phosphorous doped with a resistivity of 0.17 ohm cm and a thickness of 2.5  $\mu$ m.

5 The first major step, shown in Figures 6 and 7, is the formation of a trench mask atop the epitaxial layer 60, and the etching of trenches 23, 24 and others, to a depth of about 1200 $\text{\AA}$ . The trench sidewalls are then prepared for gate oxidation and an initial sacrificial oxidation is carried out, leaving the device as shown in Figure 7.

10 Thereafter, and as shown in Figure 8, gate oxide layers 25 and 26 are grown inside the trench walls (and over the upper silicon surface). The gate oxide is grown for 30 minutes at 950°C O<sub>2</sub>/TCA.

15 Next, and as also shown in Figure 8, polysilicon is grown over the upper surface of the wafer and into the trenches as polysilicon gates 28 and 29. The polysilicon is grown to a thickness of about 7,500 $\text{\AA}$ . After the polysilicon is grown, it is made conductive by a boron implant with a dose of 1E14 and an energy of 80 20 KeV. This implant is followed by an anneal and drive step at 1050°C for 60 minutes in nitrogen. A mask is then applied to etch the polysilicon off the top of the active device surface (the termination is not described herein and is conventional) and the wafer then appears as 25 shown in Figure 8.

30 Thereafter, there is a polyoxidation step at 975°C for 40 minutes at O<sub>2</sub>/TCA to grow oxide atop the poly in each trench. The source implant step is then carried out to form the P<sup>+</sup> implants shown in Figure 9, which will become the P<sup>+</sup> source regions 30 to 33 of Figure 2. The source implant in Figure 9 is a boron implant at a dose of 2E15 and an energy of 50 KeV. Next,

as shown in Figure 9, a TEOS insulation layer 35, 36 is deposited atop the wafer to a thickness of 7,500Å.

5 Next, and as shown in Figure 10, a source drive is carried out to drive the P<sup>+</sup> source regions into the silicon, driving at 850°C for 30 minutes in nitrogen.

10 The final steps applied to the wafer of Figure 10 produce the structure shown in Figure 2, and include a contact mask step to open the contact windows, followed by the formation of N<sup>++</sup> layer 51 to improve the contact between the silicon and the aluminum source metal. The region 51 may be formed by a phosphorous implant with a dose of 1E15 and energy of 50 KeV. After suitable metal deposition preparation, aluminum front metal 40 is applied by sputtering to a thickness of 8 µm.

15 Thereafter, the wafer 20 is reduced in thickness to 210 µm as by grinding, and the back metal or drain 41 is suitably deposited, forming the device as shown in Figure 2.

20 In carrying out the above process, a trench width of 0.6 µm and a mesa width of 1.8 µm have been used. Other dimensions can be selected. Further, a square cell has been used, although a stripe can be used. After completion of the wafer, die have been formed with dimensions of 75 mils x 90 mils with 88% being active 25 area. Larger die sizes of 102 mils (2.591 mm) x 157 mils (3.988 mm) with 92% being active area, have also been used.

30 Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. It is preferred, therefore, that the present invention be

limited not by the specific disclosure herein, but only by the appended claims.